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A new, kinematically anomalous H I component in the spiral galaxy NGC 2403

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ABSTRACT

We discuss new, high sensitivity H I observations of the spiral galaxy NGC 2403 which show extended emission at anomalous velocities with respect to the ‘cold’ disk. This ‘anomalous’ gas component ($\sim 1/10$ of the total H I mass) is probably located in the region of the halo and rotates more slowly ($\sim 20\text{--}50$ km s $^{-1}$) than the gas in the disk. Moreover, it shows a distortion in the velocity field that we interpret as a large-scale radial motion ($10\text{--}20$ km s $^{-1}$ inflow) towards the centre of the galaxy. The most likely explanation for its origin and kinematics seems to be that of a galactic fountain. There is, however, a significant part of the anomalous gas which seems to be moving contrary to rotation and is difficult to understand in such a picture. These anomalous gas complexes discovered in NGC 2403 may be analogous to the High Velocity Clouds of our Galaxy. They may be rather common in spiral galaxies and not have been detected yet for lack of sensitivity.

Subject headings: galaxies: individual (NGC 2403) — galaxies: structure — galaxies: kinematics and dynamics — galaxies: halos — galaxies: ISM

1. Introduction

In recent years neutral hydrogen observations of spiral galaxies at different inclination angles have been made with the aim of studying the 3D distribution of the gas and the associated kinematical signature. The study of face-on galaxies has led to the detection of vertical motions and of ‘holes’ in the H I distribution that are thought to be produced by the expansion of large bubbles (‘superbubbles’) around stellar associations. Detailed studies have been presented for some nearby spirals like M101 (Kamphuis 1993) and dwarf galaxies like Ho II (Puche et al. 1992). The study of the edge-on galaxy NGC 891 has revealed the presence of neutral gas emission up to 5 kpc from the plane (Swaters, Sancisi, & Van der Hulst 1997). Detailed modeling of the H I layer of this galaxy has led to the conclusion that this emission comes from an extended H I ‘halo’ with a mass of $\sim 6 \times 10^8 M_\odot$ (15% of the total H I mass) and slower rotational velocities (by about 25 to 100 km s⁻¹) than the gas in the disk. Optical spectroscopy has revealed the presence of a very thick layer (some kpc) of diffused ionized gas (DIG) in edge-on spiral galaxies (Hoopes, Walterbos, & Rand 1999) and also this ionized gas seems to show a vertical gradient in the rotation velocity. In NGC 5775 the velocity drops down to about the systemic velocity at distances of ~ 5 kpc from the plane (Rand 2000).

Thick layers of gas, large vertical motions, and rotation velocity gradients in the vertical direction, all suggest a complex circulation of gas, at different phases, between disk and halo of spiral galaxies. In the classic model of galactic fountain (Shapiro & Field 1976; Bregman 1980), a continuous gas circulation is produced by supernova explosions and stellar winds that cause the mostly ionized gas to leave the plane of the disk. Once out of the plane, the ejected ionized gas is expected to move further outwards mainly because of the pressure gradient and to decrease its circular velocity conserving its angular momentum. After cooling, clouds of neutral gas fall down towards the disk and acquire an inward motion.

We present here new, high sensitivity H I observations of NGC 2403, a nearby spiral with ongoing active star formation and the presence of bright H II regions. These observations bring new evidence bearing on fountain dynamics and indeed show halo gas with slower rotation and give the first indications of a radial flow towards the centre of the galaxy. However, we also detect emission from H I which apparently moves contrary to rotation and is therefore difficult to place in the classical fountain picture.

2. The ‘anomalous’ gas

The nearby spiral galaxy NGC 2403 (Figure 1) is an excellent candidate for a deep study of the density distribution and the kinematics of H I. It has an extended H I layer (the H I radius down to a column density of $\sim 0.2 M_{\odot}\text{pc}^{-2}$ is about 22 kpc ($1' \simeq 1$ kpc), the Holmberg radius is 13 kpc) with regular kinematics and a symmetric, flat rotation curve. Furthermore, it is viewed at an intermediate inclination angle of 60° . This offers the advantage, with respect to the edge-on and face-on views, that information is obtained on both the motion and the density structure in the vertical direction.

We have observed NGC 2403 with the VLA¹ in C configuration and a total integration time of 48 hours. These very high sensitivity observations (the noise in the $15''$ resolution data is 0.17 mJy/beam per channel with a velocity resolution of 10.3 km s^{-1}) have revealed very faint H I emission, unknown from previous observations. Figure 1 shows the resulting total H I map and velocity field; a more detailed report of the observations will be given elsewhere (Fraternali et al., in preparation).

The position-velocity (p-v) diagram along the major axis of NGC 2403 (Figure 2) clearly shows systematic asymmetries in the line profiles with respect to the rotation curve (white squares). The profiles display faint wings of emission (we refer to them as the ‘beard’) on the side of lower rotation velocities, extending systematically towards the systemic velocity. Such a pattern is similar to that found in edge-on galaxies and also in objects observed at relatively low angular resolution. However, NGC 2403 is sufficiently far from edge-on ($i = 60^{\circ}$) and our VLA observations have sufficiently high angular resolution. It is therefore excluded that we are seeing here a component of the ‘cold’ disk which is projected along the line of sight because of inclination or resolution effects.

The ‘beard’ was already known from previous WSRT observations of NGC 2403 obtained by Sicking (1997), and was interpreted by Schaap, Sancisi, & Swaters (2000) as due to gas located in the halo region of NGC 2403 and rotating more slowly than the gas in the plane. They constructed 3D models of the H I layer assuming a two-component structure: a thin disk and a thicker layer rotating more slowly. Such simple models, with a mass ratio between halo and disk components of about 15% and a difference in rotation velocity of about 25 km s^{-1} , were able to reproduce the main features of the observed p-v diagram.

With our new data the observational picture is considerably improved and new facts are uncovered. The ‘beard’ is much more extended and, completely unexpected, some emission

¹The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities.

also shows up in the upper right and lower left quadrants of Figure 2 (forbidden for rotation). Emission in these quadrants means non-circular motions (apparently counter-rotating). We refer to the gas responsible for such emission as the ‘forbidden’ gas and refer to all the gas found at anomalous velocities (including the forbidden part) as the anomalous gas.

The total mass of the anomalous gas is $\sim 3 \times 10^8 M_\odot$ (of which just $\sim 6\text{--}7 \times 10^6 M_\odot$ forbidden), which corresponds to 10% of the total H I mass of NGC 2403, and to 0.3% of its total dynamical mass. The location on the sky of the anomalous gas can be seen (shaded areas) in Figure 3 where we show four representative channel maps. From them it is clear that the distribution of the anomalous gas is characterized by several clumpy features. The upper left and lower right panels show the forbidden gas (arrows) respectively in the S–E and the N–W side of the galaxy. The other two panels, for velocities closer to systemic, show a remarkable coherent filament, 8 kpc long, with a total H I mass of $\sim 1 \times 10^7 M_\odot$.

In order to study the properties of the anomalous gas we have separated it from the ‘cold’ thin H I disk by assuming that the line profiles for the thin disk are represented by a Gaussian function. We have fitted such functions at each position and subtracted them from the data. Similar results have been obtained by folding the higher velocity sides of the observed line profiles about the profile-peak velocities (i.e. the rotation velocities) and subtracting them from the data cube (more details are given in Fraternali et al., in preparation). The mean rotation velocity derived for the anomalous H I is about $20\text{--}50 \text{ km s}^{-1}$ lower than the disk rotation.

Figure 1 (bottom right) shows the velocity field for the anomalous H I, to be compared with that derived for the thin disk (bottom left). The kinematics of the anomalous gas is clearly dominated by differential rotation, but its projected kinematical minor and major axes appear to be rotated in a counter-clockwise sense with respect to those of the regular disk. The effect is more pronounced in the turn of the minor axis (thick line) with the result that minor and major axes are non-orthogonal. An obvious interpretation of such a pattern is that of a non-zero radial component of the gas velocity.

The kinematics of the anomalous gas has been studied by constructing detailed models of the H I layer of NGC 2403. This has been done using the well known method of tilted rings and adopting a two-component structure similar to that used for the models of Schaap et al. (2000). The main difference is that in our case all the parameters (rotation velocity, H I column density, position and inclination angles) of the tilted ring model are derived from the data, both for the thin disk and for the anomalous gas. For the velocity dispersion of the anomalous gas the data indicate values of $20\text{--}50 \text{ km s}^{-1}$, whereas for the cold disk the values are around $8\text{--}12 \text{ km s}^{-1}$. Figure 4 shows a p-v diagram parallel to the minor axis and centred on the major axis at $1'$ (South-East) from the galaxy centre. This position was

chosen to illustrate the effects of radial motions. The diagram shows asymmetries in the ‘V’ shape especially visible at the low density levels which trace the anomalous gas. The two models labeled with ‘in-flow’ and ‘out-flow’ were obtained by adding, for the anomalous component, a constant radial motion of -20 km s^{-1} and $+20 \text{ km s}^{-1}$ respectively. It is evident from Figure 4 that there is a preference for inflow of the anomalous H I towards the centre of the galaxy as opposed to an outflow or no radial motion at all. Traces of the forbidden H I emission, not explained by the inflow model, are visible near the centre at velocities from 50 to 100 km s^{-1} .

3. Discussion and Conclusions

Slowly rotating H I halos as proposed by Swaters et al. (1997) for the edge-on spiral galaxy NGC 891 and as indicated by the anomalous gas in the present observations of NGC 2403 may be common in spiral galaxies. Indeed, a similar pattern as shown here for NGC 2403 has also been seen in recent WSRT observations of the spiral NGC 4559 (Oosterloo et al., in preparation). The fact that this was unknown until recently is partly due to the poor sensitivity of previous observations.

What is the origin of the anomalous gas? Our observations of NGC 2403 have revealed two new facts. The first is the change in position angle of the projected minor axis of the velocity field of the anomalous gas and a straightforward explanation for this is a radial flow of gas towards the centre of the galaxy. The second fact, probably the most surprising one, is the presence of the forbidden gas. This gas has projected differences from the rotation velocity of up to 150 km s^{-1} but, despite this large spread, it remains confined within the radial velocity range (-10 to $+275 \text{ km s}^{-1}$) of the galaxy rotation. Its nature is not clear but its location in the central bright 4 kpc of the galaxy (see Figures 2 and 3) suggests a connection with the high star formation activity.

If the picture of galactic fountain is correct, our detection of the anomalous gas with a radial flow towards the centre of NGC 2403 may be a direct detection of gas in the final ‘infalling’ stage of the fountain. There may be problems in explaining, in such a picture, long coherent structures like the 8 kpc filament. However, the main difficulty with a standard fountain interpretation lies in the presence of the forbidden gas. In order to explain that, a new approach and different assumptions for the fountain dynamics, for instance no conservation of angular momentum, may be necessary. We are now pursuing the study of this phenomenon with deep optical spectroscopy and X-ray *Chandra* observations of the central regions of NGC 2403.

An alternative explanation for the non-orthogonality of the axes could be that of non-circular (elliptical) orbits as expected in a triaxial halo potential. Such a possibility is, however, not supported by the harmonic analysis of the velocity field of NGC 2403 (Schoenmakers, Franx, & de Zeeuw 1997) that suggests that the disk of NGC 2403 is axisymmetric to a fairly high degree.

The overall pattern and the large-scale regularity of both the ‘beard’ and the forbidden gas as seen in the p-v map (Figure 2) suggest that the anomalous gas forms one coherent structure. It seems to ‘know’ about the general pattern of disk rotation and to follow it closely as a broad band somewhat shifted to lower rotational velocities. If we interpret this lower rotation as an asymmetric drift phenomenon (Binney & Tremaine 1989), we can estimate the velocity dispersion of the anomalous gas. With the derived rotation curves of the disk and of the anomalous gas and neglecting gas pressure effects we get a value for the velocity dispersion in the central regions of up to about 50 km s^{-1} , not incompatible with that observed for the forbidden gas.

Finally, the anomalous gas found in NGC 2403 may be similar to a class of the High Velocity Clouds observed in the Milky Way (Wakker & Van Woerden 1997). Although the distances and masses of HVCs are still a matter of debate it seems fair to suggest that we have detected in NGC 2403 a population of H I clouds of the same type as those intermediate and high velocity clouds which are thought to be closely associated with the Galaxy. The recent determination of a very low metal abundance for some of these clouds (Wakker et al. 1999) indicates that a part of the galactic high velocity gas may be *primordial* (Oort 1970). A similar origin might also be advocated for the anomalous gas found in NGC 2403. In such a picture, however, the regularity of the pattern (following the rotation) and the concentration of the forbidden gas in the optically bright (stellar) part of the system would be difficult to understand.

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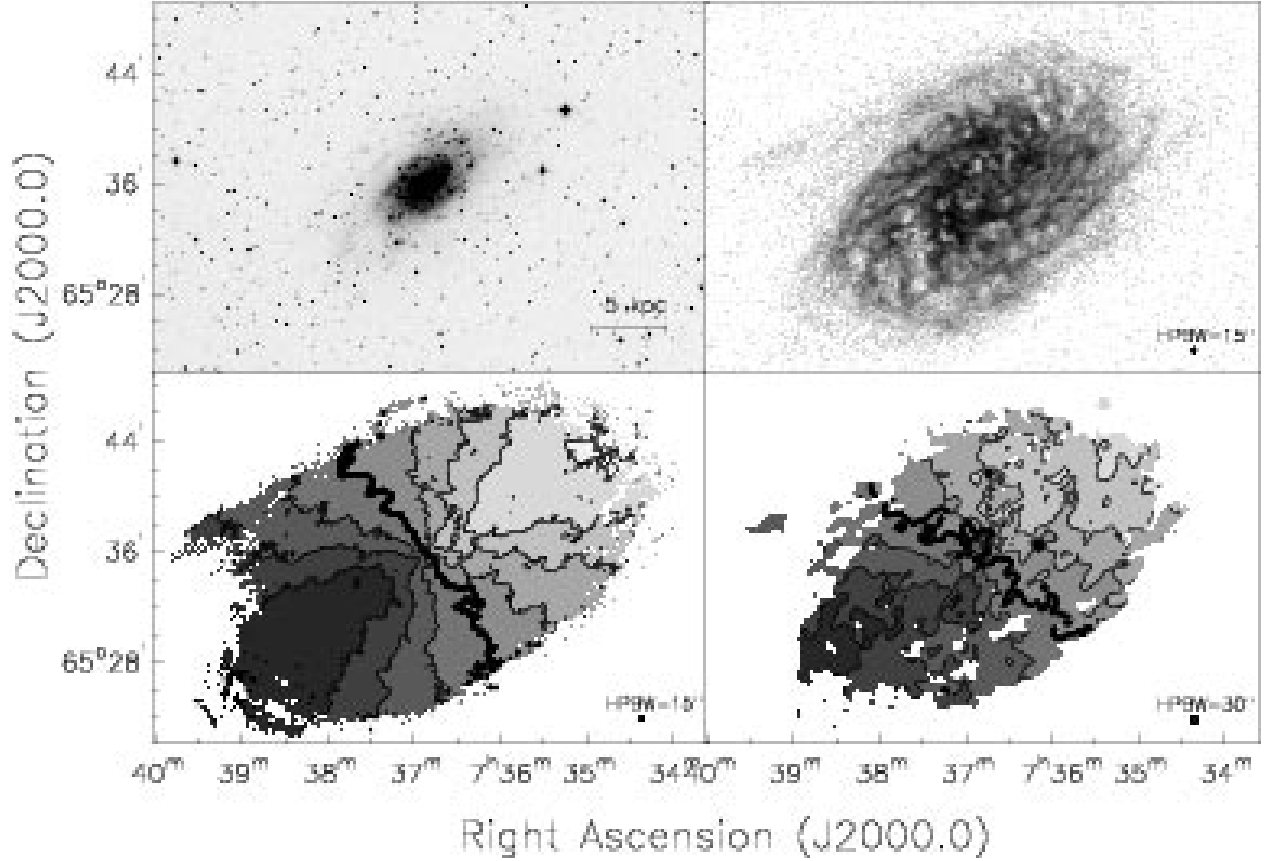


Fig. 1.— NGC 2403. Upper panels: optical image (DSS) and total H I density map (VLA). The column density range in the total H I map is $2 \times 10^{19} - 1 \times 10^{21} \text{ cm}^{-2}$. Bottom panels: velocity field of the cold thin disk (left) and of the anomalous gas (right). Contour steps in both velocity fields are 30 km s^{-1} . The receding side is darker, and the thick line shows the kinematical minor axis. The systemic velocity is 133 km s^{-1} . All plots are on the same scale.

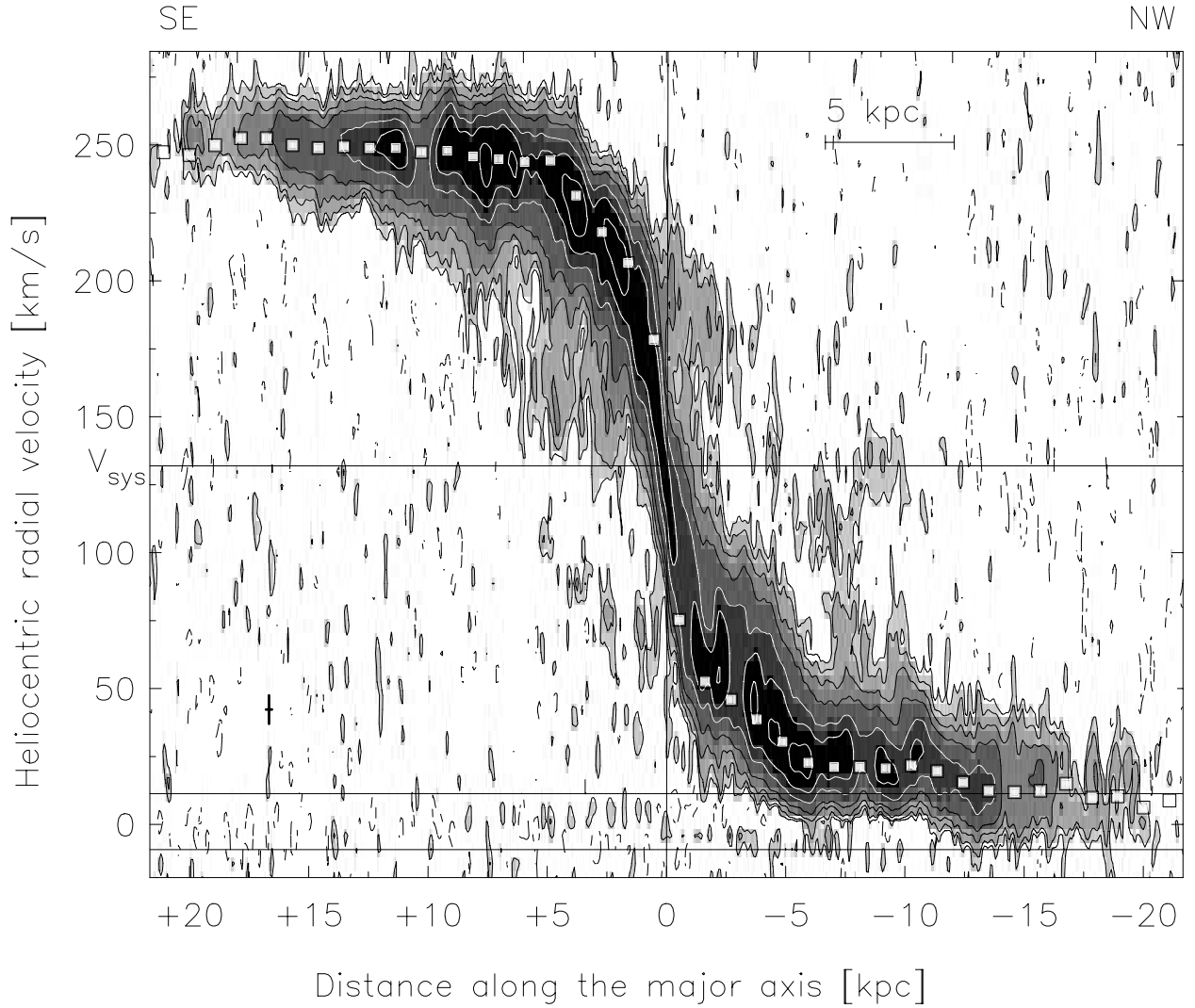


Fig. 2.— H I position-velocity diagram along the major axis (p.a. = 124° , $V_{\text{sys}} = 133 \text{ km s}^{-1}$) of NGC 2403 ($45''$ wide slice). The beam size is $\sim 15''$. The contours are $-0.4, 0.4, 1, 2, 4, 10, 20, 40 \text{ mJy/beam}$, the r.m.s. noise is 0.17 mJy/beam . The two horizontal lines mark the channels contaminated by emission from our Galaxy. The white squares show the (projected) rotation curve.

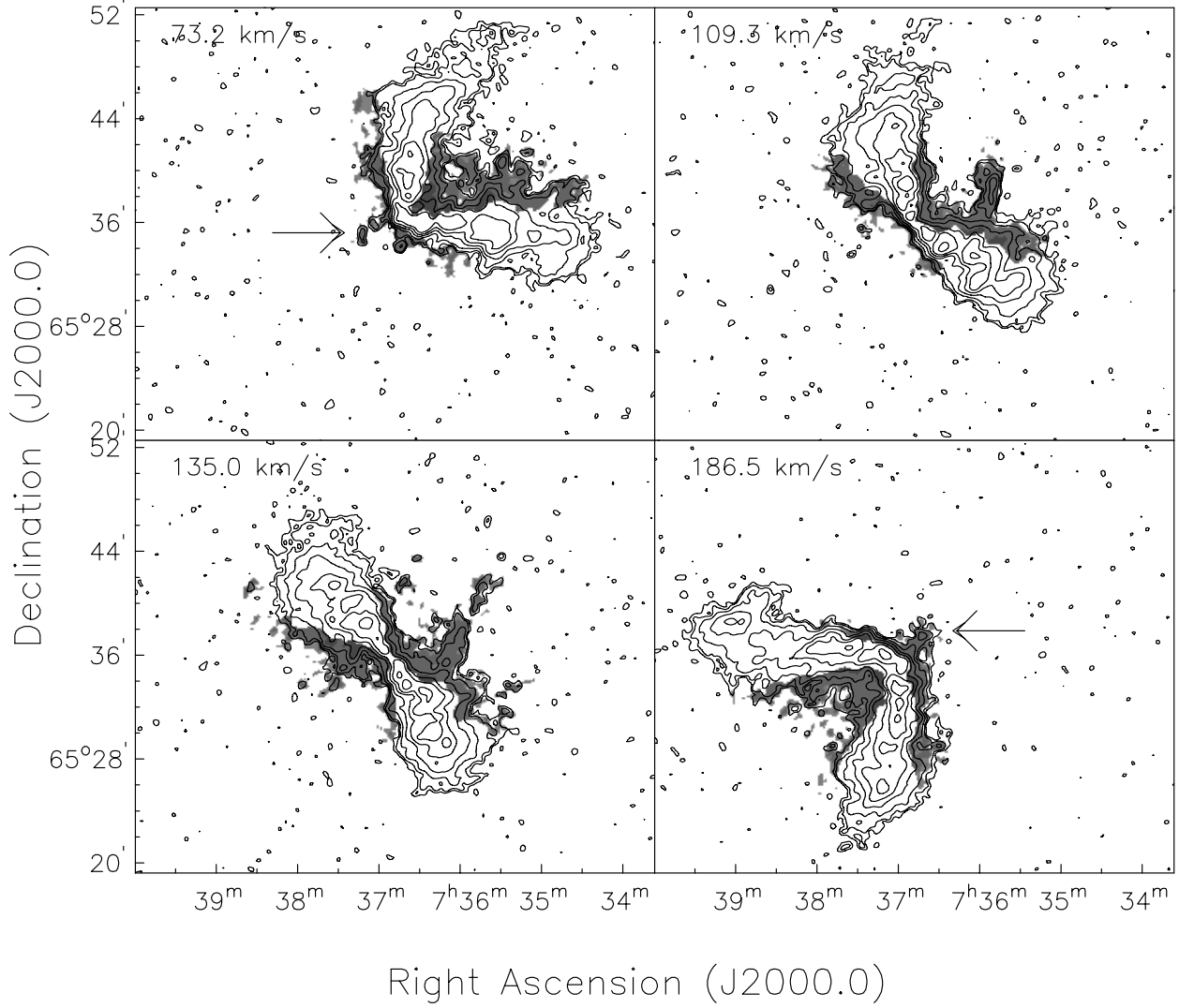


Fig. 3.— Four representative H I channel maps for NGC 2403. The contour levels are -0.6 , 0.6 , 1 , 2 , 4 , 10 , 20 , 40 mJy/beam, the r.m.s. noise is 0.22 mJy/beam. The beam size is $30''$. The shading shows the anomalous gas. The upper left and lower right panels show the forbidden gas (arrows) while the central panels show a remarkable 8 kpc long H I filament.

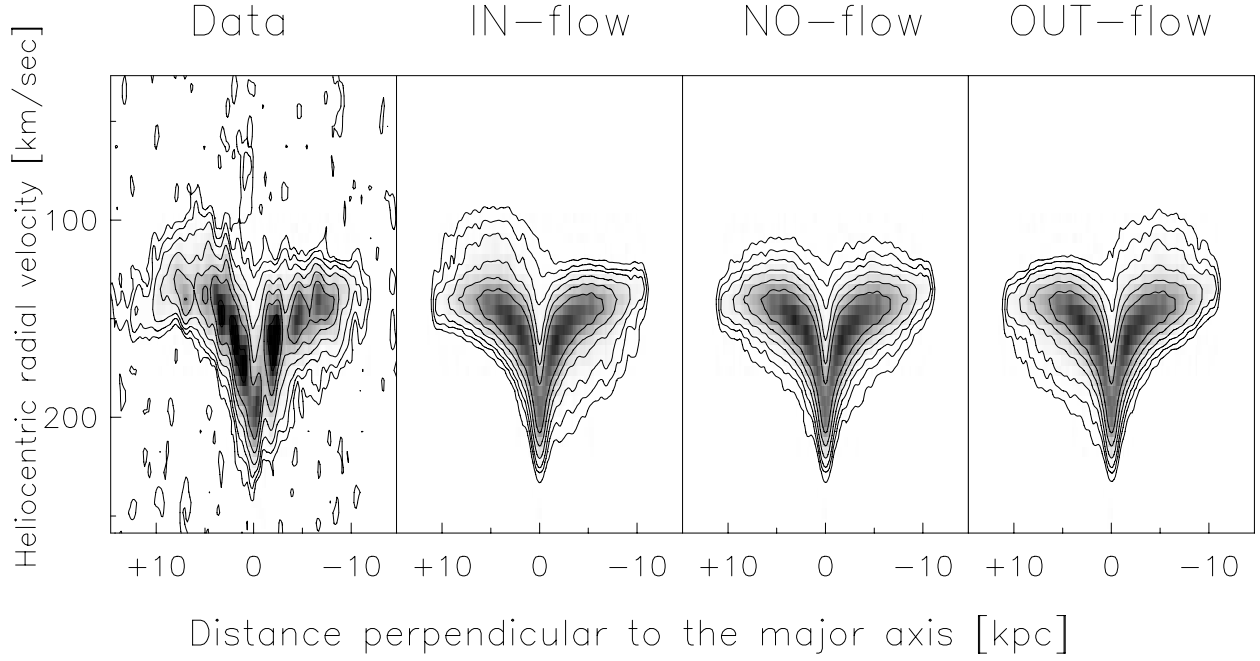


Fig. 4.— Position-velocity diagram parallel to the minor axis centred on the major axis at $1'$ S–E from the centre of the galaxy. The contour levels are $-0.5, 0.5, 1, 2, 4, 10, 20, 40$ mJy/beam, the r.m.s. noise is 0.22 mJy/beam, and the beam size is $30''$. The three models are characterized by lower rotation + radial in-flow, no-flow, and radial out-flow.